We claim:

1. A method for separating isotopes of an actinide element comprising steps of:

providing a composition comprising molecules comprising an actinide element, wherein at least some of the molecules include a first isotope of the actinide element and at least some of the molecules include a second isotope of the actinide element;

exposing the molecules comprising the actinide element to reducing activity of actinide element reducing microorganisms, thereby allowing formation of a precipitate comprising the actinide element, wherein the precipitate contains a higher proportion of the second isotope relative to the first isotope than was present in the original composition, thereby effecting a separation of the first and second isotopes; and

effecting an increased separation of the first and second isotopes present in the precipitate using any suitable process.

2. The method of claim 1, wherein the exposing step comprises:

combining the composition and the microorganisms in a vessel together with culture medium, thereby producing a culture; and

maintaining the culture for a time sufficient to allow formation of a precipitate.

3. The method of claim 1, further comprising the step of :

separating the precipitate from unprecipitated molecules containing the actinide element.

4. The method of claim 3, wherein the step of separating comprises collecting the precipitate.

5. The method of claim 3, wherein the step of separating comprises collecting the precipitate and the microorganisms.

6. The method of claim 5, further comprising the step of treating the microorganisms to remove molecules containing adsorbed, unreduced actinide element atoms therefrom.

7. The method of claim 1, wherein the exposing step is performed for a time selected to achieve optimum isotope separation.

8. The method of claim 7, wherein the actinide element is uranium, and the optimum isotope separation results in maximum $\delta^{235}U$ for the precipitate.

9. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 80% of the actinide element.

10. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 60% of the actinide element.

11. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 40% of the actinide element.

12. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 20% of the actinide element.

13. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 10% of the actinide element.

14. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 5% of the actinide element.

15. The method of claim 1, wherein the exposing step is performed for a time selected to achieve reduction of less than 1% of the actinide element.

16. The method of claim 1, wherein the exposing step is performed for a time selected so that at least 20% of the actinide element remains in solution.

17. The method of claim 1, wherein the exposing step is performed for a time selected so that at least 40% of the actinide element remains in solution.

18. The method of claim 1, wherein the exposing step is performed for a time selected so that at least 60% of the actinide element remains in solution.

19. The method of claim 1, wherein the exposing step is performed for a time selected so that at least 80% of the actinide element remains in solution.

20. The method of claim 1, wherein the exposing step is performed for a time selected so that at least 90% of the actinide element remains in solution.

21. The method of claim 1, wherein the exposing step is performed for a time selected so that at least 95% of the actinide element remains in solution.

22. The method of claim 1, further comprising the step of:
determining the isotope content of the precipitate.

23. The method of claim 1, wherein the effecting step comprises:
converting the actinide element present in the second composition into a form suitable for repetition of the exposing step; and
repeating the exposing step using the converted actinide element as a starting material, thereby effecting an increased separation of the first and second isotopes.

24. A composition produced according to the method of claim 23.

25. The composition of claim 24, wherein the actinide element is uranium and the precipitate comprises uraninite.

26. The method of claim 23, wherein the step of converting comprises:
oxidizing at least some of the molecules comprising the actinide element in the precipitate.

27. The method of claim 26, wherein the oxidizing step is performed by exposing the molecules to ozone, peroxide, other chemical oxidants, or by application of an oxidizing potential.

28. The method of claim 26, wherein the oxidizing step comprises:
exposing the molecules comprising the actinide element in the precipitate to ozone in a solution; and further comprising the step of treating the solution with air to remove the ozone.

29. The method of claim 26, wherein the oxidizing step comprises:
applying an oxidizing potential to the precipitate using an electrode.

30. The method of claim 26, wherein the step of oxidizing causes solubilization of the oxidized molecules, resulting in a solution suitable for use as a starting material.

31. A composition produced according to the method of claim 26.

32. The composition of claim 31, wherein the actinide element is uranium and the precipitate comprises uraninite.

33. The method of claim 26, further comprising the steps of repeating the method until a desired degree of isotope separation is achieved.

34. The method of claim 33, wherein the desired degree of isotope separation results in a composition comprising between 3% and 4% ^{235}U.

35. The method of claim 33, wherein the desired degree of isotope separation results in a composition comprising between 4% and 20% ^{235}U.

36. The method of claim 23, further comprising the step of :

separating the precipitate from unprecipitated molecules containing the actinide element prior to the oxidizing step.

37. The method of claim 1, wherein the steps are performed in batch mode.

38. The method of claim 1, wherein the steps are performed in continuous mode.

39. The method of claim 1, further comprising the step of:

desorbing remaining unreduced molecules containing the actinide element from the microorganisms.

40. The method of claim 1, wherein the microorganisms are present in a medium that is separated from the composition by a semi-permeable membrane during the exposing step, which semi-permeable membrane allows diffusion of the actinide element containing molecules but does not permit passage of the microorganisms.

41. The method of claim 40, wherein the exposing step comprises allowing the composition to flow continuously past the semi-permeable membrane, thereby

allowing diffusion of the actinide element containing molecules so as to expose them to the reducing activity of the microorganisms.

42. The method of claim 41, wherein the exposing step comprises allowing the composition and the medium containing the microorganisms to flow continuously past the semi-permeable membrane, thereby allowing diffusion of the actinide element containing molecules so as to expose them to the reducing activity of the microorganisms.

43. The method of claim 42, wherein the composition and the medium containing the microorganisms flow in opposite directions.

44. The method of claim 1, further comprising the step of:

immobilizing the microorganisms prior to performing the exposing step.

45. The method of claim 44, wherein the step of immobilizing the microorganisms comprises:

fixing the microorganisms to a solid support.

46. The method of claim 44, wherein the microorganisms are contained within a semi-permeable membrane or membranes.

47. The method of claim 44, wherein the exposing step comprises allowing the composition to traverse the immobilized microorganisms.

48. The method of claim 1, wherein the actinide element is uranium.

49. The method of claim 48, wherein the precipitate comprises uraninite.

50. The method of claim 48, wherein the microorganisms reduce uranium from the U(VI) state to the U(IV) state.

51. The method of claim 48, wherein the first isotope is heavier than the second isotope.

52. The method of claim 48, wherein the first uranium isotope is U-238.

53. The method of claim 48, wherein the second uranium isotope is U-235.

54. The method of claim 48, wherein the first uranium isotope is U-238 and the second uranium isotope is U-235.

55. The method of claim 1, wherein the method achieves a separation factor of at least 1.02.

56. The method of claim 1, wherein the method achieves a separation factor of at least 1.06.

57. The method of claim 1, wherein the method achieves a separation factor of at least 1.10.

58. The method of claim 1, wherein the actinide element is plutonium.

59. The method of claim 1, wherein the actinide element is neptunium.

60. The method of claim 1, wherein the composition comprises an electron donor.

61. The method of claim 1, wherein the molecules comprising the actinide element are provided together with a counter ion, wherein the counter ion is not an electron accepting species that competes with the actinide element for reduction by the microorganisms.

62. The method of claim 61, wherein the counter ion can serve as a substrate for metabolism by the microorganisms under anaerobic conditions.

63. The method of claim 61, wherein the counter ion is selected from the group consisting of: lactate, acetate, and chloride.

64. The method of claim 1, wherein the microorganisms are metal or sulfate reducing bacteria.

65. The method of claim 1, wherein the microorganisms are facultative aerobes.

66. The method of claim 1, wherein the microorganisms are anaerobes.

67. The method of claim 1, wherein the microorganisms are members of a bacterial genus selected from the group consisting of: *Clostridium*, *Shewanella*, *Geobacter*, *Pyrobaculum*, *Desulfotomaculum*, and *Desulfovibrio*.

68. The method of claim 67, wherein the microorganisms are members of bacterial genus *Shewanella*.

69. The method of claim 67, wherein the microorganisms are members of bacterial strain *Shewanella oneidensis*.

70. The method of claim 67, wherein the microorganisms are selected from the group consisting of *Clostridium* sp., *Deinococcus radiodurans* R1, *Geobacter chapelleii, Geobacter hydrogenophilus* H2, *Geobacter hydrogenophilus* H2, *Geobacter* H4, *Geobacter* TACP-2, *Geobacter* TACP-3, *Pyrobaculum islandicum*, *Shewanella alga*, *Shewanella saccharophila*, *Desulfotomaculum reducens* MI-1, *Desulfovibrio desulfuricans*, and *Desulfovibrio vulgaris*.

71. The method of claim 1, wherein the microorganisms are present at a concentration of between approximately 10^7 and 10^9 per milliliter during the exposing step.

72. The method of claim 1, wherein the microorganisms overexpress a gene encoding a protein that reduces the actinide element.

73. The method of claim 72, wherein the gene encodes a cytochrome c protein.

74. The method of claim 73, wherein the cytochrome c is a cytochrome c3.

75. The method of claim 1, wherein the microorganisms overexpress a gene encoding a protein involved in a pathway leading to reduction of the actinide element.

76. The method of claim 1, wherein the microorganisms express an altered cytochrome c protein, which altered cytochrome c protein displays an increased ability to reduce the actinide element relative to a wild type version of the protein.

77. The method of claim 1, wherein the microorganisms express an altered version of a gene encoding a protein involved in a pathway leading to reduction of the actinide

element, which altered cytochrome c protein displays an increased ability to reduce the actinide element relative to a wild type version of the protein.

78. The method of claim 1, wherein the exposing step takes place in a medium substantially free of counterions capable of forming insoluble salts with unreduced molecules of the actinide element.

79. The method of claim 78, wherein the concentration of any counterion capable of forming an insoluble salt with unreduced molecules of the actinide element is less than 10% of the concentration of unreduced molecules of the actinide element in the medium.

80. The method of claim 78, wherein the concentration of any counterion capable of forming an insoluble salt with unreduced molecules of the actinide element is less than 5% of the concentration of unreduced molecules of the actinide element in the medium.

81. The method of claim 78, wherein the concentration of any counterion capable of forming an insoluble salt with unreduced molecules of the actinide element is less than 1% of the concentration of unreduced molecules of the actinide element in the medium.

82. The method of claim 78, wherein the medium lacks significant amounts of phosphate.

83. The method of claim 1, wherein the exposing step is performed in the presence of an organic polymer.

84. The method of claim 1, further comprising the step of:

culturing the microorganisms under aerobic conditions prior to the maintaining step and performing the maintaining step under anaerobic conditions.

85. A composition produced according to the method of claim 1.

86. A method for separating isotopes of an actinide element comprising steps of:

providing a composition comprising molecules comprising an actinide element, wherein at least some of the molecules include a first isotope of the actinide element and at least some of the molecules include a second isotope of the actinide element;

exposing the molecules comprising the actinide element to reducing activity of actinide element reducing microorganisms, thereby allowing reduction of a portion of the molecules comprising the actinide element to form reduced molecules, wherein the reduced molecules contain a higher proportion of the second isotope relative to the first isotope than was present in the original composition, thereby effecting a separation of the first and second isotopes; and

effecting an increased separation of the first and second isotopes present in the reduced molecules using any suitable process.

87. The method of claim 86, wherein the actinide element is uranium.

88. The method of claim 86, wherein the microorganisms are metal or sulfate reducing bacteria.

89. The method of claim 86, wherein the microorganisms are thermophilic bacteria, and wherein the exposing step is performed at a temperature above 50°C.

90. The method of claim 86, further comprising the step of:

extracting some or all of the reduced molecules from the composition.

91. The method of claim 90, further comprising the step of:

reextracting the reduced actinide containing molecules into an aqueous phase and either reoxidizing them or collecting them.

92. The method of claim 90, wherein the extracting step comprises:

forming an extractable organic complex comprising reduced actinide molecules using an organic ligand; and

extracting the extractable complex into an organic phase or onto a solid support coated with an organic material.

93. The method of claim 92, wherein the organic ligand comprises thenoyltrifluoroacetone.

94. The method of claim 86, wherein the microorganisms are present in a medium that is separated from the composition by a semi-permeable membrane during the exposing step, which semi-permeable membrane allows diffusion of the actinide element containing molecules but does not permit passage of the microorganisms.

95. The method of claim 94, wherein the exposing step comprises allowing the composition to flow continuously past the semi-permeable membrane, thereby allowing diffusion of the actinide element containing molecules so as to expose them to the reducing activity of the microorganisms.

96. The method of claim 94, wherein the exposing step comprises allowing the composition and the medium containing the microorganisms to flow continuously past the semi-permeable membrane, thereby allowing diffusion of the actinide element containing molecules so as to expose them to the reducing activity of the microorganisms.

97. The method of claim 86, wherein the effecting step comprises:

converting the actinide element present in the second composition into a form suitable for repetition of the exposing step; and

repeating the exposing step using the converted actinide element as a starting material, thereby effecting an increased separation of the first and second isotopes.

98. The method of claim 97, wherein the step of converting comprises:

oxidizing at least some of the molecules comprising the actinide element in the precipitate.

99. A composition produced according to the method of claim 86.

100. The composition of claim 99, wherein the actinide element is uranium.

101. A method for separating isotopes of an actinide element comprising steps of:

providing a composition comprising molecules comprising an actinide element, wherein at least some of the molecules include a first isotope of the actinide element and at least some of the molecules include a second isotope of the actinide element;

incubating the molecules comprising the actinide element with an actinide reducing enzyme obtained from an actinide element reducing microorganism, thereby allowing formation of a precipitate comprising the actinide element, wherein the precipitate contains a higher proportion of the second isotope relative to the first isotope than was present in the original composition, thereby effecting a separation of the first and second isotopes; and

effecting an increased separation of the first and second isotopes present in the precipitate using any suitable process.

102. The method of claim 101, further comprising the step of :

separating the precipitate from unprecipitated molecules containing the actinide element.

103. The method of claim 102, wherein the step of separating comprises collecting the precipitate.

104. The method of claim 101, wherein the exposing step is performed for a time selected to achieve optimum isotope separation.

105. The method of claim 101, wherein the actinide element is uranium, and the optimum isotope separation results in maximum $\delta^{235}U$ for the precipitate.

106. The method of claim 101, further comprising the step of:

determining the isotope content of the precipitate.

107. The method of claim 101, wherein the effecting step comprises:

converting the actinide element present in the second composition into a form suitable for repetition of the exposing step; and

repeating the exposing step using the converted actinide element as a starting material, thereby effecting an increased separation of the first and second isotopes.

108. A composition produced according to the method of claim 107.

109. The composition of claim 108, wherein the actinide element is uranium and the precipitate comprises uraninite.

110. The method of claim 107, wherein the step of converting comprises:

oxidizing at least some of the molecules comprising the actinide element in the precipitate.

111. The method of claim 110, wherein the oxidizing step is performed by exposing the molecules to ozone, peroxide, other chemical oxidants, or by application of an oxidizing potential.

112. The method of claim 110, wherein the oxidizing step comprises:

exposing the molecules comprising the actinide element in the precipitate to ozone in a solution; and further comprising the step of treating the solution with air to remove the ozone.

113. The method of claim 110, wherein the oxidizing step comprises:

applying an oxidizing potential to the precipitate using an electrode.

114. The method of claim 110, wherein the step of oxidizing causes solubilization of the oxidized molecules, resulting in a solution suitable for use as a starting material.

115. A composition produced according to the method of claim 110.

116. The composition of claim 115, wherein the actinide element is uranium and the precipitate comprises uraninite.

117. The method of claim 110, further comprising the steps of repeating the method until a desired degree of isotope separation is achieved.

118. The method of claim 117, wherein the desired degree of isotope separation results in a composition comprising between 3% and 4% ^{235}U.

119. The method of claim 117, wherein the desired degree of isotope separation results in a composition comprising between 4% and 20% ^{235}U.

120. The method of claim 107, further comprising the step of :

separating the precipitate from unprecipitated molecules containing the actinide element prior to the oxidizing step.

121. The method of claim 101, wherein the steps are performed in batch mode.

122. The method of claim 101, wherein the steps are performed in continuous mode.

123. The method of claim 101, wherein the enzyme is at least partially purified.

124. The method of claim 101, wherein an electron donor is present during the incubating step.

125. The method of claim 101, wherein the actinide reducing enzyme is a cytochrome c enzyme.

126. The method of claim 125, wherein the cytochrome c is a cytochrome c3.

127. The method of claim 125, wherein the cytochrome c is at least partially purified.

128. The method of claim 101, wherein hydrogenase obtained from an actinide element reducing microorganism is present during the incubating step.

129. The method of claim 128, wherein the hydrogenase is at least partially purified.

130. The method of claim 128, wherein an electron donor in addition to hydrogenase is present during the incubating step.

131. The method of claim 101, wherein an electron donor other than hydrogenase is present during the incubating step.

132. The method of claim 101, wherein a material providing a nucleation site for uraninite formation is provided during the incubating step.

133. The method of claim 101, wherein the incubating step is performed in a fixed enzyme reactor.

134. A composition produced according to the method of claim 101.

135. The composition of claim 134, wherein the actinide element is uranium and the precipitate comprises enriched uraninite.

136. A method of separating isotopes of an actinide element comprising steps of:

providing a composition comprising molecules comprising an actinide element, wherein at least some of the molecules include a first isotope of the actinide element and at least some of the molecules include a second isotope of the actinide element;

incubating the molecules comprising the actinide element with an actinide reducing enzyme obtained from an actinide element reducing microorganism, thereby allowing reduction of the actinide element to form a reduced actinide element;

removing the reduced actinide element;

further incubating the reduced actinide element, thereby allowing formation of a precipitate comprising the reduced actinide element, wherein the precipitate contains a higher proportion of the second isotope relative to the first isotope than was present in the original composition, thereby effecting a separation of the first and second isotopes; and

effecting an increased separation of the first and second isotopes present in the precipitate using any suitable process.

137. The method of claim 136, wherein the enzyme is a cytochrome c enzyme.

138. The method of claim 137, wherein the cytochrome c is a cytochrome c3.

139. The method of claim 137, wherein the cytochrome c is at least partially purified.

140. The method of claim 136, wherein hydrogenase obtained from an actinide element reducing microorganism is present during the incubating step.

141. The method of claim 140, wherein the hydrogenase is at least partially purified.

142. The method of claim 140, wherein an electron donor in addition to hydrogenase is present during the incubating step.

143. The method of claim 136, wherein an electron donor other than hydrogenase is present during the incubating step.

144. A composition produced according to the method of claim 136.

145. The composition of claim 144, wherein the actinide element is uranium and the precipitate comprises enriched uraninite.

146. A method for separating isotopes of an actinide element comprising steps of:

providing a composition comprising molecules comprising an actinide element, wherein at least some of the molecules include a first isotope of the actinide element and at least some of the molecules include a second isotope of the actinide element;

incubating the molecules comprising the actinide element with an actinide reducing enzyme obtained from an actinide element reducing microorganism, , thereby allowing reduction of a portion of the molecules comprising the actinide element to form reduced molecules, wherein the reduced molecules contain a higher proportion of the second isotope relative to the first isotope than was present in the original composition, thereby effecting a separation of the first and second isotopes; and

effecting an increased separation of the first and second isotopes present in the precipitate using any suitable process.

147. The method of claim 146, wherein the actinide element is uranium.

148. The method of claim 146, wherein the microorganisms are metal or sulfate reducing bacteria.

149. The method of claim 146, wherein the microorganisms are thermophilic bacteria, and wherein the exposing step is performed at a temperature above 50°C.

150. The method of claim 146, further comprising the step of:

extracting some or all of the reduced molecules from the composition.

151. The method of claim 150, further comprising the step of:

reextracting the reduced actinide containing molecules into an aqueous phase and either reoxidizing them or collecting them.

152. The method of claim 150, wherein the extracting step comprises:

forming an extractable organic complex comprising reduced actinide molecules using an organic ligand; and

extracting the extractable complex into an organic phase or onto a solid support coated with an organic material.

153. The method of claim 152, wherein the organic ligand comprises thenoyltrifluoroacetone.

154. A composition prepared according to the method of claim 146, wherein the actinide element is uranium.